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NAVAL POSTGRADUATE SCHOOL
Monterey, California

The Automatic Control Specialty
in the
Mechanical Engineering Department

D. L. Smith
R. H. Nunn
October 1985

Progress Report for period
Oct 1984 - Sep 1985

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of coursework in automatic controls for the Mechanical Engineering (ME) Department which took place during FY85 as a continuation of work begun in FY84. The report describes the development of two required courses designed to satisfy the Educational Skill Requirement in controls as levied by NAVSEA. In addition, the development of elective coursework and thesis research is discussed.

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I. Introduction

This report describes the development of coursework in automatic controls for the Mechanical Engineering (ME) Department which took place during FY 85 as a continuation of work begun in FY 84 [Ref. 1]. This work was motivated by the Educational Skill Requirement (ESR) levied by NAVSEA as follows:

> "[Teach] basic understanding of automatic control systems and their application to Integrated Propulsion Plant Control."

The ME Dept. approach to the ESR was to identify two required ME courses to teach the basics. In addition, the department began to investigate elective courses which could support an automatic controls thesis specialty option. Further, the total offering was to be consistent with a widespread practice of controls teaching. This report is organized into six sections: The present introductory section is followed by a brief summary of previous work; the third and fourth sections discuss FY 85 course and laboratory development, respectively; the fifth section presents related research; and the last section contains conclusions.

II. Previous Work

Work accomplished in FY 84 led to the following conclusions:

1. Two required courses in controls are needed to satisfy the ESR. There are so many basic concepts in systems and controls which need to be introduced in these courses that some understanding of applications will only be achieved through a period of study equivalent to approximately two quarter-courses in length.
2. A specialization level of understanding (4XXX, graduate level course) is not appropriate to either of the required courses, as per the ESR.

3. ME faculty should teach both required courses. Automatic control is a fundamental area of mechanical engineering and, as such, all of the ME faculty in the area of design should be able to teach the two courses.

4. Some "hands-on" controller investigation by the students is desirable to complete the students' understanding of basic concepts.

5. A design-oriented approach to the second required course should be taken in order to keep the students in touch with the goal of control design: a successfully controlled system (e.g. a controlled power plant in accordance with specifications).

Based on the preceding conclusions, the following courses were recommended:

<u>Required</u>

ME3801 Linear Automatic Control.
(to replace EC3413, Fudamentals of Automatic Control)
Introduction to linear controller analysis methods. Classical methods for single-input-single-output (SISO) plants.

ME3802 Marine Control Systems.
(to replace ME4802, Marine Propulsion Control)
Introduction to controller design practice. Linearization of nonlinear plants. Linear controllers for multiple-input multiple-output (MIMO) plants. Study of Integrated Throttle Control on the DD963 and other developmental MIMO controllers.

<u>Elective</u>

ME4801 Fluid Power Control.
Analysis and design of hydraulically actuated control sytems.

ME4803 Advanced Topics in Controls.
System Identification (parameter identification). Nonlinear controller design. Design of microprocessor-based controllers.

ME4902 Reading Course in Controls. Selected, specialized topics for individual study with the professor.

In addition, it was recommended that thesis topics in controls be identified within the areas of marine propulsion, servomechanisms, and robotics.

III. FY85 Course Development

ME3801, Linear Automatic Control, is being offered for the first time during AY 86-1. The course syllabus is included as Appendix I. The objective of the course is to provide the students with the basic analytical tools necessary to evaluate a controlled system composed of a linear controller and a linear, SISO plant. The course is taught from a fundamental viewpoint with general application studies.

ME4802, Marine Propulsion Control, is the course which is now taught to satisfy the ESR regarding integrated control. This course has evolved into a design-oriented course, compared to ME3801 which is analysis-oriented, with special emphasis on control of marine propulsion plants. The course was taught twice during AY 85 and the latest course outline is included in this report as Appendix II.

The study of the design problem in ME4802 was begun by examining Navy Controls Specifications, both the general specifications for ships of the U.S. Navy and the Proposed DDG51 design specifications. A DD963 marine gas turbine propulsion plant was then evaluated to identify cause and effect relationships, plant inputs and outputs, and control variables. The implementation of Integrated Throttle Control on the DD963 was next discussed in order to illustrate a contemporary control strategy implementation (a recent research report was used to do this, "The Naval Gas Turbine Ship Propulsion Dynamics and Control Systems Research and Development Program," SNAME Trans., Vol. 90, 1982, pp. 321-338). Following this specific introductory material, a more general approach was taken to the remainder of the course.

The course approach for ME4802 was developed to address the modeling and control design tasks in the order that they must be faced by a controls designer. In this way, it was felt that the students can learn what must be done, when it is done, and how it is done by studying the controller design process. Specifically, the following design tasks were discussed:

1. Specification for control design.
2. Evaluation of plant function.
3. Plant mathematical modeling.
4. Plant model validation - open loop simulation and experimentation.
5. Selection of control strategy.
6. Selection of actuators and sensors.
7. Dynamic modeling of actuators and sensors.
8. Selection of controller action.
9. Theoretical controller design.
10. Controller validation - closed loop simulation and comparison to specifications.
11. Prototype.

The design process was repeated four times for four different propulsion plants. The course emphasized tasks 1, 2, 5, 8, 9 and 10 for the various controller/plant combinations. Plant models were supplied in the interest of expediency (tasks 3 and 4), as were actuator and sensor models (tasks 6 and 7). The propulsion plant was assumed to be given and unchangeable, thus allowing the class to fully concentrate on the controller design process.

The theory content of the course was developed around the idea that the plant is usually nonlinear, but that it can be linearized. This is a good approach for marine propulsion systems. Consequently, linear controller design methods were taught based on plant input/output classification. For single-input-single-output (SISO) plants, PID and compensation methods were discussed. For multiple-input-multiple-output (MIMO) plants, transfer matrix compensators and linear quadiatic regulators were discussed.

The course was concluded with a discussion of the implementation of digital controllers. The following hardware topics were discussed: analog-to-digital conversion of sampled data; sampling rate effects; computer/controller recursion formulas; and digital-to-analog conversion of controller signals.

The present "laboratories" for ME4802 are really ten homework projects, each of which consists of general theory homework problems from the course text plus one or more controller design tasks for a marine gas turbine propulsion plant. During the quarter, each student completed four different controller designs for the plant. In order to give the students a feeling of reality, the design tasks were related to the NPS marine gas turbine propulsion emulator (ref. 2). Copies of the projects are included as Appendix III. Further work needs to be done to support these homework projects with true lab projects and "hands on" hardware involvement (more about this below).

The elective course ME4801, Fluid Power Control, has been successfully offered in the past the only change has been in lab development which will be discussed below.

ME 4512, Advanced Dynamics, has not been taught for some time at the NPS. However, a growing student interest in robotics at the school has caused a renewed student interest in the course material. The course is now under review and will be offered in the winter quarter, AY86-2.

ME4803, Advanced Topics in Controls, is in the formative stage. It could be offered as student interest indicates and as lab equipment becomes available.

IV. Laboratory Development

Lab development is proceeding in conjunction with the NAVSEA program for lab hardware improvement now being conducted at the NPS. There are two phases to this program:

Phase I. Hardware was purchased to support the fluid power control course, ME4801. The hardware included:

1. One Hewlett Packard HP85 controller and data acquisition system.
2. A fluid power bench for synthesizing hydraulic control experiment setups.
3. Measurement instrumentation for measuring fluid power variables.
4. An armdraulic table-top instruction robot.

Supporting this hardware purchase, a series of experiments has been designed to illustrate some important features of hydraulic controls operation. Five experiments and their objectives were defined as follows (for more details, see Appendix IV).

1. Hydraulic actuator static performance. To determine the static performance of a typical rotary actuator (pump driven motor).
2. Flow control valve static performance. To characterize a flow control valve of typical configuration (e.g. four-way, three-end, critical center or open center spool valve).
3. Dynamic performance of a hydraulic power element, valve controlled position. To evaluate the performance of a hydraulic power element, to determine its performance characteristics (leakage coefficients, hydraulic spring rate, damping ratio, etc,) and to compare these

results with theory.

4. Dynamic performance of a position-control servomechanism. To examine the dynamic performance of the servo and to evaluate the effects of various design options.

5. Dynamic performance of a velocity-control servomechanism. To examine the dynamic performance of the servo and to evaluate the effects of various design options.

Phase II. This phase of the NAVSEA/NPS Lab hardware improvement program is now in the proposal stage. Hardware items for experiments to support ME4802 (soon to be ME3802, Marine Control Systems) and ME4803, Advanced Controls Topics, have been proposed. The following experiments are envisioned:

A. For ME4802, Marine Propulsion Control:

1. Diesel control lab. This will be a table-top experiment using a microprocessor-based diesel engine simulator and a programmable controller to investigate transfer matrix compensation.

2. Steam engine control lab. Another table-top apparatus will be used to simulate steam engine operation and to investigate the use of a linear quadratic regulator for control.

3. Gas turbine control lab. This experiment will investigate the implementation issues of sampling rate, A/D conversion, D/A conversion, and computer algorithms. A table-top microprocessor-based simulation of the marine gas turbine needs to be developed to conduct this experimentation.

B. For ME4803, Advanced Topics in Control, the distinguishing feature between these labs and those for ME4802 will be the emphasis on controller design. The labs for ME4802 will be more instructor prepared, "cookbook" fashion, and will allow the students to concentrate on the input-output relationships between the controller and the plant for various controller types. The labs for ME4803 will require the students to investigate the implementation issues in controller design. Two types of labs will be developed:

1. Microprocessor-based controller lab. To develop an understanding of the power and limitations computer/controllers.
2. Analog controller lab. To study the power and limitations of analog controllers.

V. Related Research

ME Department research in marine propulsion control has been looking into issues of control of diesel and marine gas turbine systems. The following theses have been advised during FY85:

1. "Marine Propulsion Load Simulation," P. N. Johnson, MSME Thesis, June 1985.
2. "Modeling of Marine Gas Turbine Components," J. Roger, MSME Thesis, December 1985 (expected).
3. "Modern Control of a Marine Gas Turbine," V. Herda, ME Engineer's Thesis, June 1986 (expected).
4. "System Identification and Control of a Internal Combustion Engine," T. Violette, MSME Thesis, December 1985 (expected).

ME Department research in robotics has been very active in response to the Naval Surface Weapons Center (NSWC/White Oak) Robotics Lab. A long-term program with NSWC is now being developed to ensure a continuing source of thesis topics for NPS students. Much of the work so far has been stimulated by the NSWC firefighter robot project. Robotics research projects during FY85 included the following:

1. "Optimal Control of Robotic Mechanisms," D. L. Smith, NPS Foundation Research.
2. "Firefighter Robot Prototype Development," D. L. Smith, NSWC proposed research for FY 86.
3. "Linearized Controller Design for a Revolute Robot," D. Lewis, MSME Thesis, December 1985 (expected).
4. "Load Measurements for a Firefighter Tool," R. Yobs, MSME Thesis, March 1986 (expected).
5. "Simulation of High Speed Dynamics for a Rigid Revolute Robot," W. McCarthy, MSME Thesis, December 1985 (expected).
6. "Modeling of Flexible Link Dynamics," R. Petroka, ME Engineer's Thesis, June 1986 (expected).

VI. Conclusions

1. The required ME coursework in controls is becoming a well-integrated two course sequence which will produce students who have a good basic understanding of automatic control systems and their application to propulsion plant control.
2. Coherent elective coursework is developing in such a way that it offers to students the opportunity to prepare for a worthwhile thesis research project based on an ME controls coursework specialization.
3. Promising research topics in marine propulsion control and robotics have begun to open up. Student interest in these problem areas seems to be quite strong, as does sponsoring lab interest.

References

1. D. L. Smith, "An Automatic Control Specialty for the Mechanical Engineering Department," NPS Report NPS69-84-012, November, 1984.

2. P. N. Johnson, "Marine Propulsion Load Emulation," NPS MSME Thesis, June 1985.

APPENDIX I

ME 3801 - LINEAR AUTOMATIC CONTROL
TENTATIVE SCHEDULE -- FALL, 1985

Week	of	Subject Matter	Assigned Reading*	Assigned Problems (Cat. B)
1	30 Sep.	Introduction. Mathematical background. Laplace Transforms.	Preface, Ch. 1, 2.	2-1 - 2.3.
2	7 Oct.	Math. background continued. Math. models of physical systems.	Ch. 2, 4. (Ch. 3)	2-4 - 2-9. 4-1 - 4.4.
3	14 Oct.	Math. models continued.	Ch. 4. (4-6)	4-5 - 4-7, 4-9 - 4.12, 4-14.
4	21 Oct.	Quiz. Controllers and basic control actions.	Ch. 5.	5-1 - 5-5.
5	28 Oct.	Basic control actions continued.	Ch. 5. (5-6)	5-6 - 5-9.
6	4 Nov.	Transient response analysis.	Ch. 6. (6-7)	6-1, 6-3 - 6-9.
7	11 Nov.	Quiz. Transient response continued. Error analysis.	Ch. 6, 7. (7-4)	6-10 - 6-13, 7-1 - 7-4.
8	18 Nov.	Root locus methods.	Ch. 8.	8-1 - 8-3, 8-5, 8-8, 8-10.
9	26 Nov.	Frequency response methods.	Ch. 9. (9-4)	9-1 - 9-3, 9-5, 9-6.
10	2 Dec.	Quiz. Frequency response methods continued.	Ch. 9.	9-8 - 9-11, 9-13.
11	9 Dec.	Design and compensation.	Ch. 10.	

* Text: Ogata, "Modern Control Engineering," Prentice-Hall, 1970. Chapters and sections in parentheses are recommended.

Hours: Tu, Th, Fri 1310-1400, Wed 1510-1700 (all in Ha 109).

APPENDIX II

NAVAL POSTGRADUATE SCHOOL
Monterey, California

ME 4802: Marine Propulsion Control (3-2)

Prerequisite: EE 3413, Fundamentals of Automatic Control

Instructor: Professor David Smith
HA 207A, X3383

Office Hours: To be announced

Course Description:
Propulsion systems overview.
Modeling and simulation of propulsion performance.
Control systems design and implementation.
Case studies of the DD 963 and DDG51.

Course Objectives:
To familiarize students with the control design process.

To introduce students to modern control methods for multivariable\systems.

To demonstrate the use of classical and modern control strategies for marine propulsion plants.

Text: Modern Control Engineering, by K. Ogata, Prentice Hall Inc., 1970. Course notes

Homework:
Assigned to aid understanding of concepts.
Will be collected.
Solutions will be posted on the second deck of Halligan Hall.

Labs: Design - oriented lab projects have been developed to allow students to practice the full control design process. Written lab reports will be submitted weekly according to the course outline. Lab reports are due at the beginning of the lab period. Selected students will orally present either homework or lab work during the scheduled lab period.

Course Grading:
Pass/Fail
Course grade will be based upon lab performance.

Course Outline

ME 4802 Marine Propulsion Conrol

Summer, 1985

Week	Date	Topic	Ref
1	7/8	• Introduction	notes
		• Control Specifications	Ch.1, 10.1
		• Plant Function:	-
		Multiport Analysis	notes
		Lab - Lab report format	
2	7/15	• SISO Plant Modeling:	-
		Linearization	11.1, 4.1, 4.3
		T.F. from data	9.9, notes
		Simulation, CSMP	notes
		Lab - Project 1: Multiport Analysis and Linearization	
3	7/22	• Classical Control Design:	-
		Control Action	5.1, 5.5
		PID Tuning	notes
		Compensation	10.1, 10.2, 10.6
		Lab - Project 1: Open Loop Plant Model Validation	
4	7/29	• Modern Control Design	14.1
		• MIMO Plant Modelling:	-
		State Space Modelling	14.2
		State Space Modelling	notes
		Lab - Project 1: Closed Loop Simulations: Classical Design Approach	
5	8/5	The Transfer Matrix	4.6
		Transfer Matrix Compensation	14.4
		Case Study - Kidd Paper	notes
		Lab - Project 2: Open Loop Simulation, Linear MIMO Plants	
6	8/12	Case Study - Kidd Paper	notes
		• Multivariable Stability Introduction:	15.1, 15.2
		Liapunov's Second Thm.	15.3
		Lab - Project 2: Transfer Matrix Design	

7	8/19	Linear Systems Analysis	15.4
		Nonlinear Systems Analysis	15.6, 15.7
		• Optimal Control Introduction:	7.3, 7.4, 16.1
		Lab - <u>Project 3</u>: Linearized Stability Analyses	
8	8/26	Controllability	16.2
		Observability	16.3
		Time Optimal Control	16.4
		Lab - <u>Project 3</u>: Controllability and Observability	
9	9/2	Holiday	-
		LQR Control	16.5
		• Computer - Based Controllers:	-
		Introduction	notes, 14.6
		Lab - <u>Project 3</u>: LQR Designs	
10	9/9	Sampling	notes
		Observers	notes
		• Model Reference, Adaptive Control	16.6, 16.7
		Lab - <u>Project 3</u>: LQR Implementations	
11	9/16	• Design Summary	notes
		• SOF's	-
		Lab - <u>Project 3</u>: Closed Loop Simulations: LQR Approach	
12	9/23	• No meetings, No Final	

APPENDIX III

ME 4802

MARINE PROPULSION CONTROL

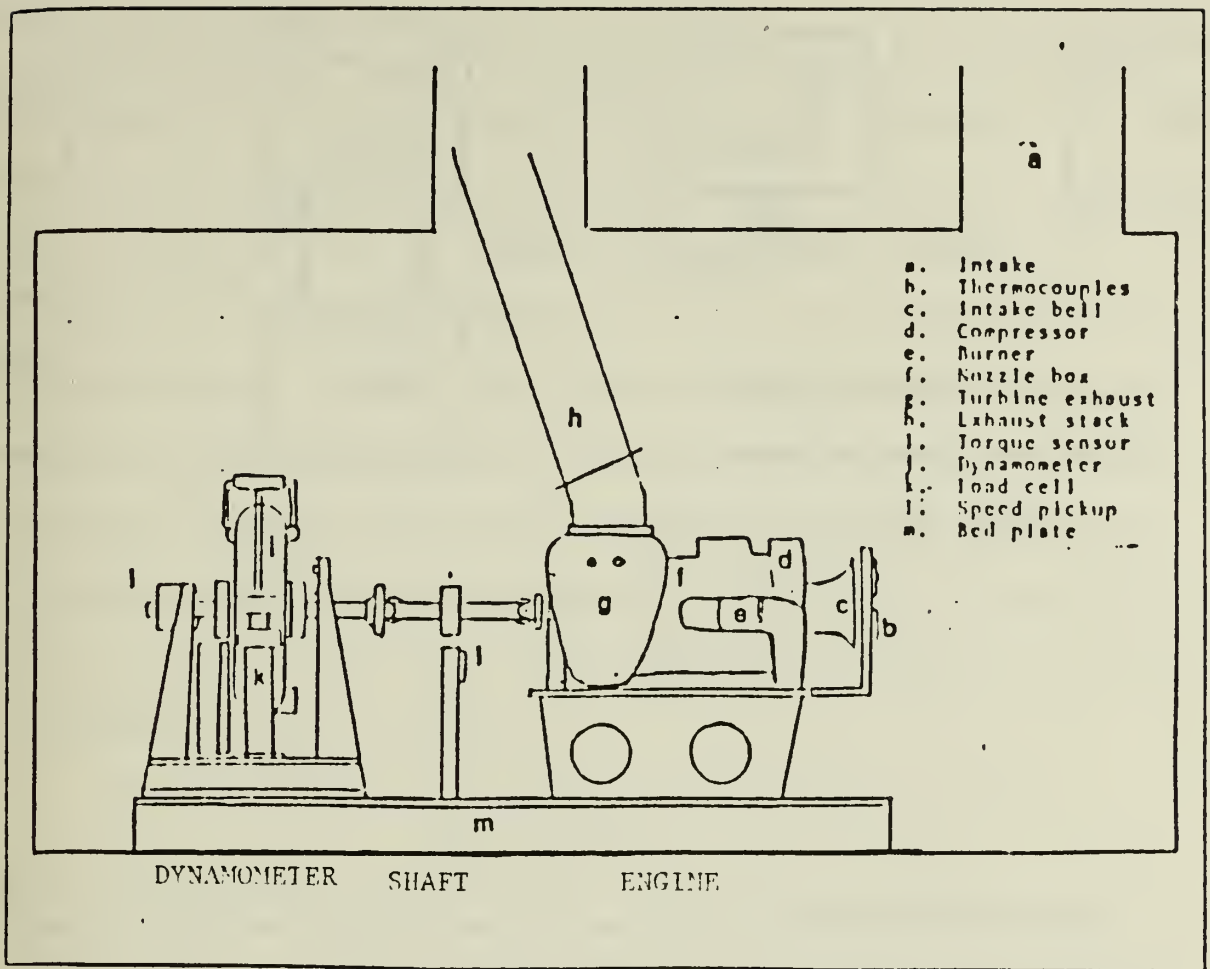
Project 1 - First Week

Classical Design:

Multiport Analysis

and Linearization

12 July 1985



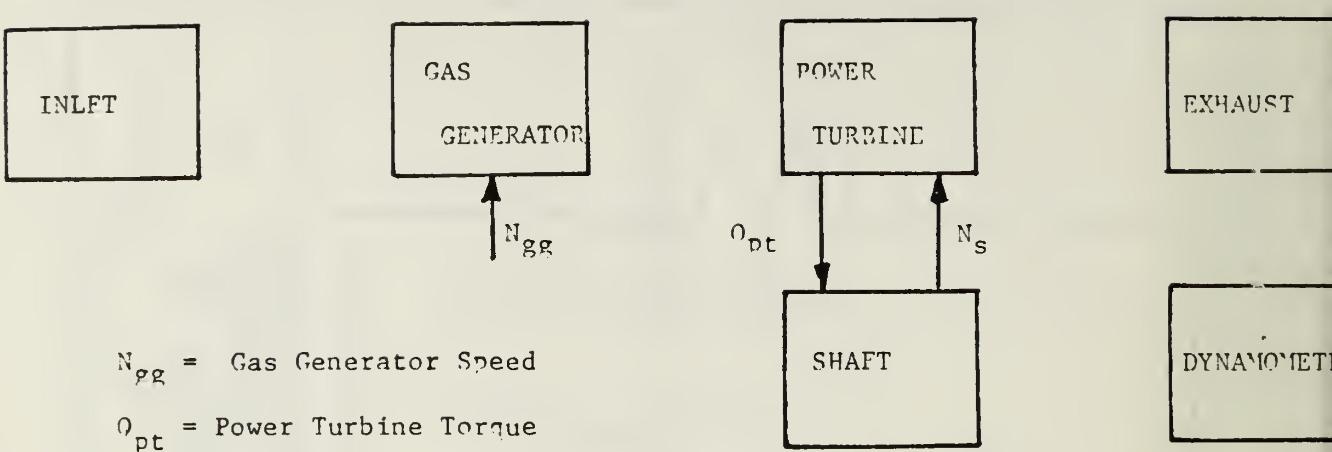
Introduction

A typical marine propulsion emulation system is shown in the figure above. In this system, a water brake dynamometer is used to load a gas turbine engine. The amount of horsepower which is dissipated by the dynamometer is proportional to the water contained in the unit and the speed at which the shaft rotates. The objectives of this three-week project are as follows:

1. To understand how the emulator is used to mimic marine propulsion dynamics.

2. To use classical controller design methods to design a controller for the dynamometer.

3. To evaluate the performance of the classical controller.



N_{gg} = Gas Generator Speed

Q_{pt} = Power Turbine Torque

N_s = Shaft Speed

1. In the figure above, the major components of the emulator have been identified for a multiport analysis. In the work for project 1 we will be considering the operation of the system at a constant water volume in the dynamometer. As shown in the figure, there is no gearing in this system. This means that the shaft speed is the same as the power turbine speed, and both of these are equal to the dynamometer speed. In this part of the project you should assume that all important inertias can be lumped into the shaft component, and complete the multiport analysis. If shaft speed is selected as the plant output, is the plant SISO?

2. Construct a multiport analysis of a machine of your choice. Comment on the interactions between components and overall plant function.

3. With the components and their inputs and outputs identified, the next step is to begin the modeling process. The assumption of all inertias being lumped into the "shaft" component allows us to use steady-state data for our component dynamic models elsewhere. For example, the steady-state performance curves for the NPS engine and dynamometer are attached. This data was gathered through a series of experiments which measured the variables in the steady-state. In our modeling, we will assume that this data also applies to dynamic, transient conditions. In this way, we can simplify the modeling task considerably. In this part of the project you must identify a linear dynamometer model of the form

$$Q_d = f_1(N_s).$$

Recall that your design work will be for the condition of constant water weight (W_w) in the dynamometer. Your linearization should be about the operating point

$$N_s =$$

$$W_w =$$

4. The shaft model will be of the form

$$\Sigma Q = J \dot{N}_s + B N_s^2 ,$$

where J is a parameter which represents the inertia of the shaft plus the reflected inertias of the other components in the system, and B is a parameter which represents the system frictional effects. In this task you should identify a linearized shaft model from the above equation in the form

$$\dot{N}_s = f_2 (Q_d, Q_{pt}, N_s).$$

The variable Q_d is the dynamometer torque in the above equation. The constants in your linearization should be evaluated about the point

$$Q_d =$$

$$Q_{pt} =$$

$$N_s =$$

5. The turbine torque/speed curve which is attached is for both the gas generator and the power turbine, e.g. it describes the engine performance. In this case, a gas generator governor has been built in which regulates gas generator speed by controlling fuel flowrate (this is why N_{gg} is the input to the gas generator rather that the fuel flowrate as discussed in class). We will assume that the governor internal to the gas generator offers no significant dynamics to the plant. This assumption will allow you to use the turbine curves to derive a linear model of the engine of the form

$$Q_{pt} = f_3(N_{gg}, N_s).$$

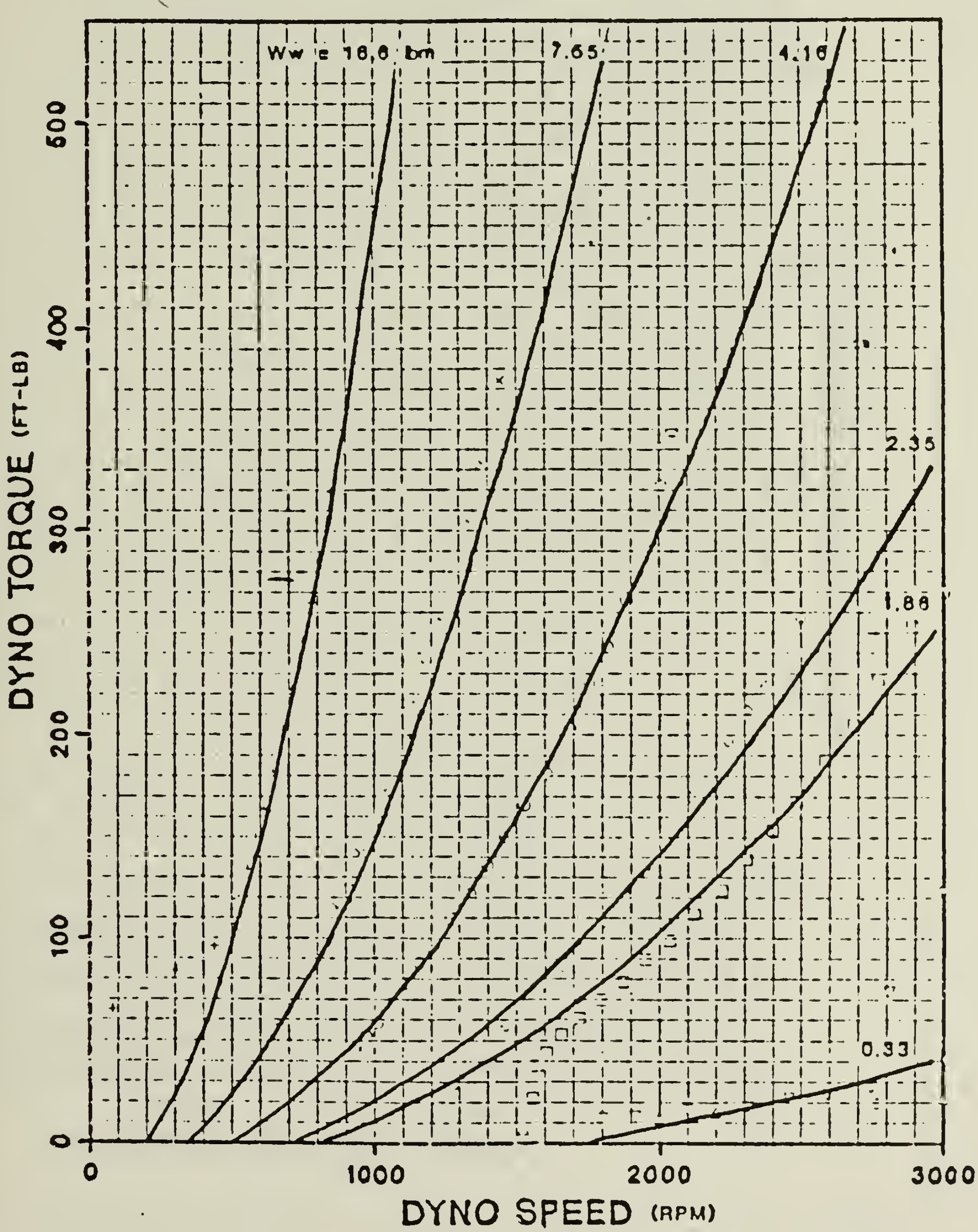
You should linearize the curves about the operating point

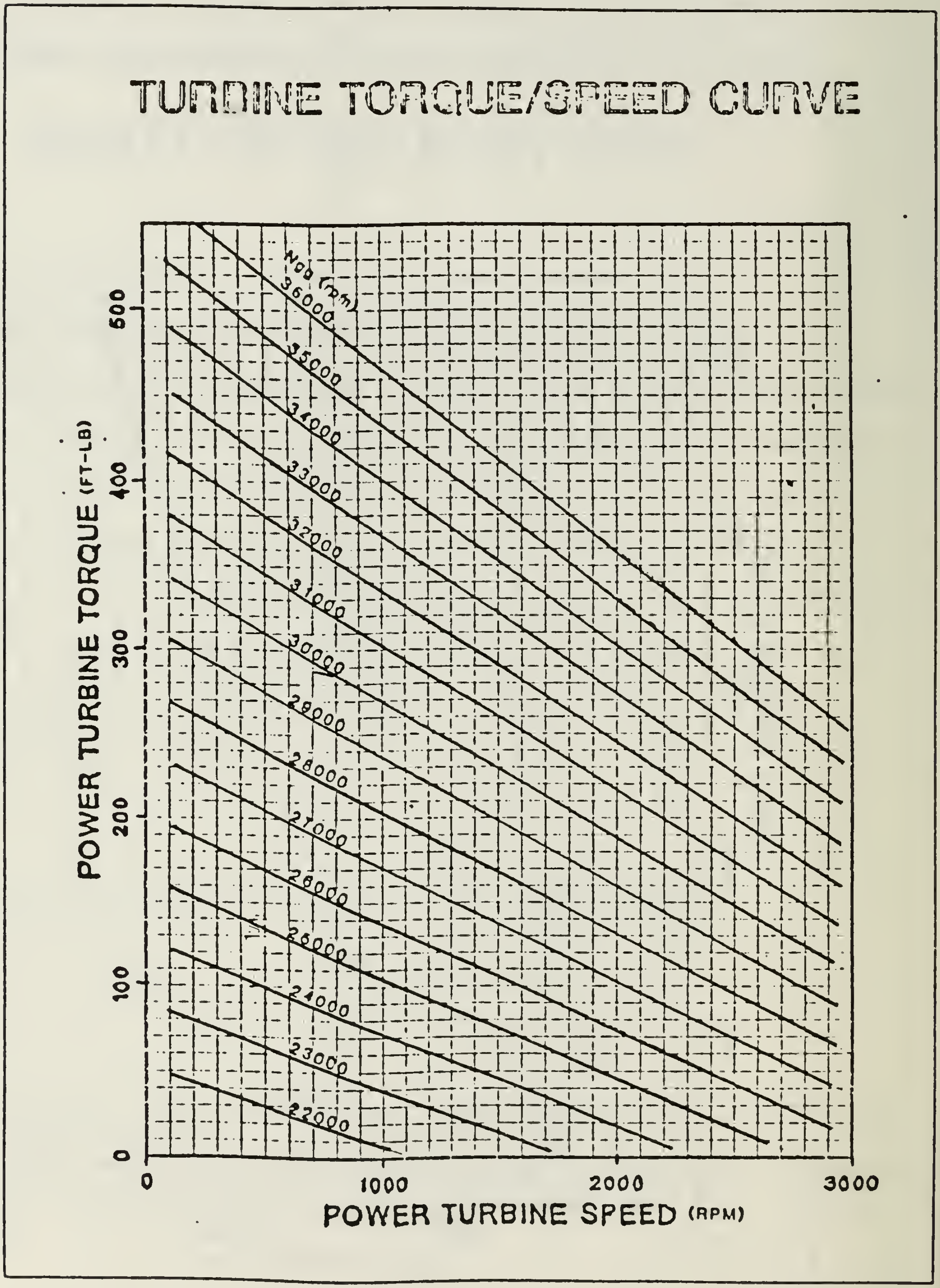
$$N_{gg} =$$

$$N_s =$$

6. Using the linear models of the plant components that you have derived, find the plant transfer function which relates the plant input (gas generator speed) to the plant output (shaft speed).

DYNO TORQUE/SPEED CURVE




TURBINE TORQUE/SPEED CURVE
POWER TURBINE TORQUE (FT-LB)
POWER TURBINE SPEED (RPM)
0
100
200
300
400
500
1000
2000
3000
Ngg (rpm)
36000
35000
34000
33000
32000
31000
30000
29000
28000
27000
26000
25000
24000
23000
22000

ME 4802

MARINE PROPULSION CONTROL

Project 1 - Second Week

Open Loop

Plant Model Validation

19 July 1985

due

26 July 1985

1. Work problem B-9-13 in <u>Modern Control Engineering</u>, pg 473.

2. At the conclusion of last weeks assignment you obtained a transfer function of the form

$$\frac{n_s}{n_{gg}} = \frac{a}{bs + c},$$

where a, b, and c are constants which depend on J and B (the fundamental constants from the shaft/inertia model) as well as the plant operating point. Use the attached plant perturbation response data to estimate the plant inertia J and the plant friction coefficient B. Be careful to watch your units, n and N are in rpm while ω is in rad/sec! To check your work you can use the weight of the shaft (64.4 lb_f, mass = 2slugs) along with the estimated J value in the relationship

$$J = \tfrac{1}{2} m r^2 .$$

Thus, your experimental value for J will allow you to calculate a corressponding value for the shaft radius, r. Is your computed radius reasonable?

3. Previous work at the NPS has shown that the emulator operating curves may be roughly curve fit by the following equations

$$Q_d = -20 + ((0.00046*(W_w/16.6)**1.3) + 4.0E-6)*(N_s**2)$$

$$Q_{pt} = (-725.76 + (0.0363642*N_{gg})) + (0.0527 - (4.455E-6*N_{gg}))*N_s$$

In this problem you should substitute the values for W_w, J, and B into the nonlinear equations in order to find the global, nonlinear plant model equation of the form

$$\dot{N}_s = f(N_s, N_{gg}) .$$

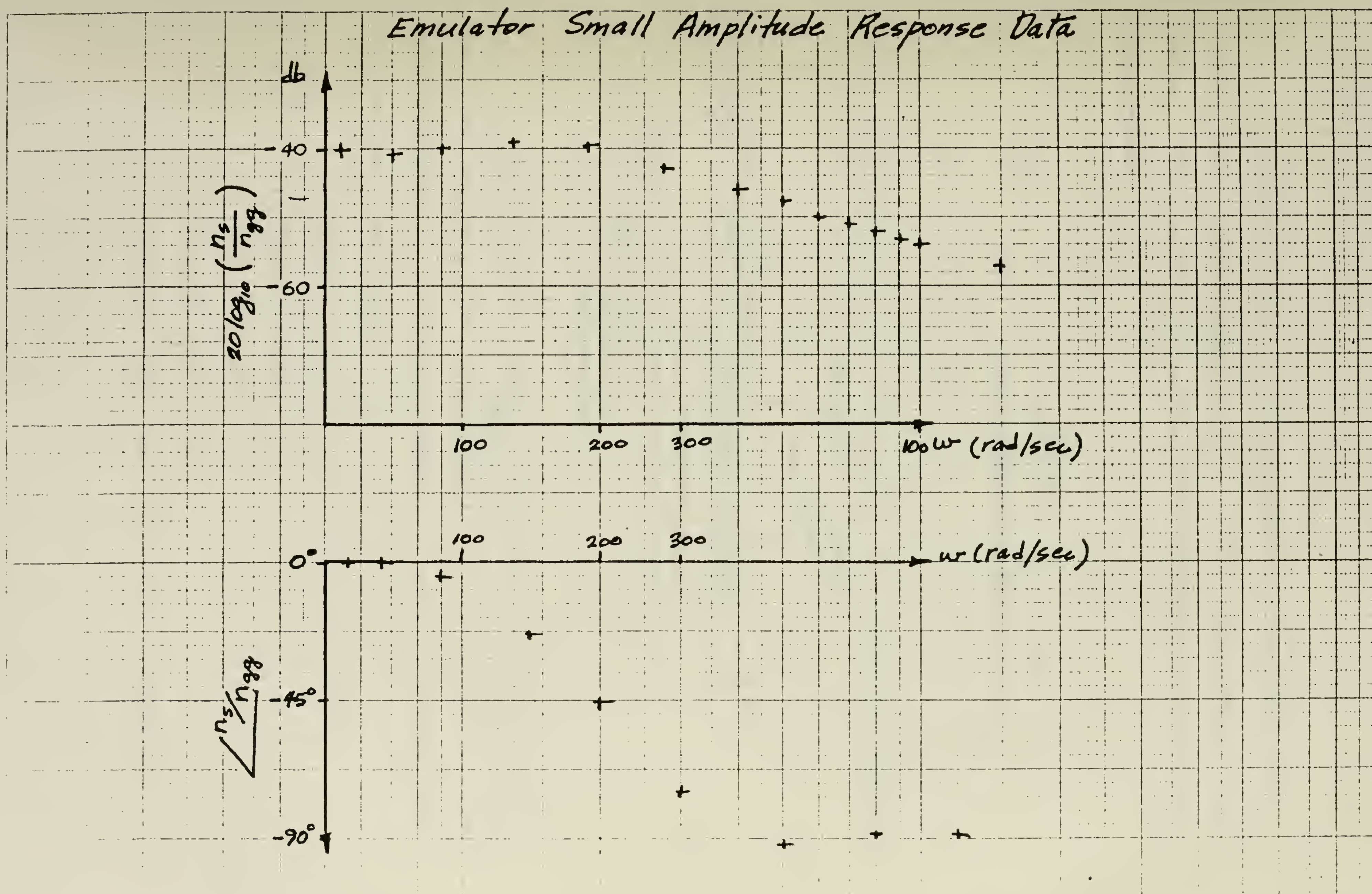
4. In this problem, the nonlinear equation above will be used to represent the "exact" dynamics of the plant and we will compare its' predictions to those from the linearized dynamics developed earlier. The means of conducting this validation of the linear model will be the simulation program CSMP. It is our goal to input the same step sizes into each model and compare the responses of N_s as a function of time.

In class we discussed the relationship

$$N_{gg} = N_{gg_i} + dN_{gg} \approx N_{gg_i} + \Delta N_{gg} ,$$

where ΔN_{gg} is a "small" step. In this problem we will associate step smallness with the ability of the linear model to accurately predict the true nonlinear behavior of the plant near the operating point. In order to investigate this, you will need to pick appropriate values for the step input. A very small N_{gg} will have small errors, both steady-state and dynamic; a very large step will have larger errors. Acceptable accuracy may be as large as $\pm$ 10% in steady-state error. In our work we will examine the growth of the errors as the step size is increased.

For this problem, you should submit two comparisons: one for a small step (steady-state error in N_s about $\pm$ 1%); and one for a step which goes to the limit of the operating range in N_s for your dynamometer water weight. Either a plus or minus step in N_{gg} is OK as long as the same step is input to the linear and nonlinear models for comparison.


Emulator Small Amplitude Response Data
db
-40
-60
$20\log_{10}\left(\frac{n_s}{n_{gg}}\right)$
100
200
300
1000 ω (rad/sec)
0°
-45°
-90°
$\angle n_s/n_{gg}$
ω (rad/sec)

ME 4802

MARINE PROPULSION CONTROL

Project 1 - Third Week

Closed Loop Simulation:

Classical Design Approach

26 July 1985

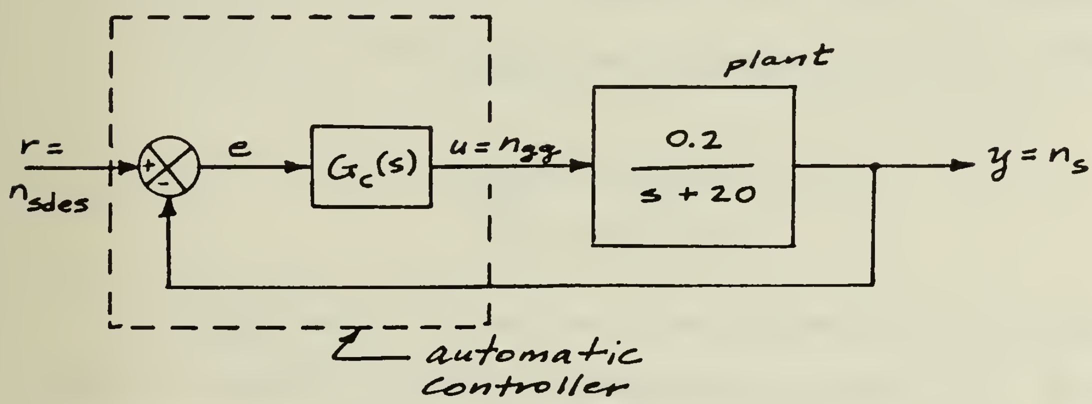
due

2 August 1985

In this lab we'll use the perturbational open-loop transfer function for the marine propulsion emulator to do some classical control design. The transfer function comes from the experimental data given out last week

$$G(s) = \frac{n_s}{n_{gg}} = \frac{0.01}{\frac{s}{20} + 1} = \frac{0.2}{s + 20},$$

and the controller that we'd like to design is a regulator of the form



As users, we will input to the regulator a desired speed n_{sdes} (note the lower case, it's a perturbation). The controller will produce the plant input n_{gg} to move the system as we desire. The objectives of this assignment are threefold:

1. To design a PID controller to meet a time domain performance specification.
2. To design a compensator to meet a frequency domain performance specification.
3. To validate a closed loop control design using CSMP.

The assignment consists of three problems:

1. What value of steady-state controller gain, K_p, is needed for a "minimum system" with G(s) so that the maximum steady-state error is 5% ?

2. As you observed last week, the time constant for the plant was very small (0.05sec.). For safety reasons, the specifications call for a closed-loop time constant no less than 0.5sec. To meet this spec you desire to slow down the closed-loop step response so that 67% of the final system steady-state output value is reached in 0.5sec. You also know that this can be accomplished by adding derivative control to the minimum system in the form

$$G_c(s) = K_p(1 + \tau_d s)$$

In this problem you should conduct an analysis to determine the value of τ_d to give the closed-loop system time constant of 0.5sec. You should hand in your analysis plus a CSMP run which validates your closed-loop design.

3. Design a series compensator for the minimum system to give a bandwidth of 200rad/sec. Are stability margins a concern for this system? Explain your answer from a sketch of G(s) on the complex plane.

ME 4802

MARINE PROPULSION CONTROL

Project 2 - First Week

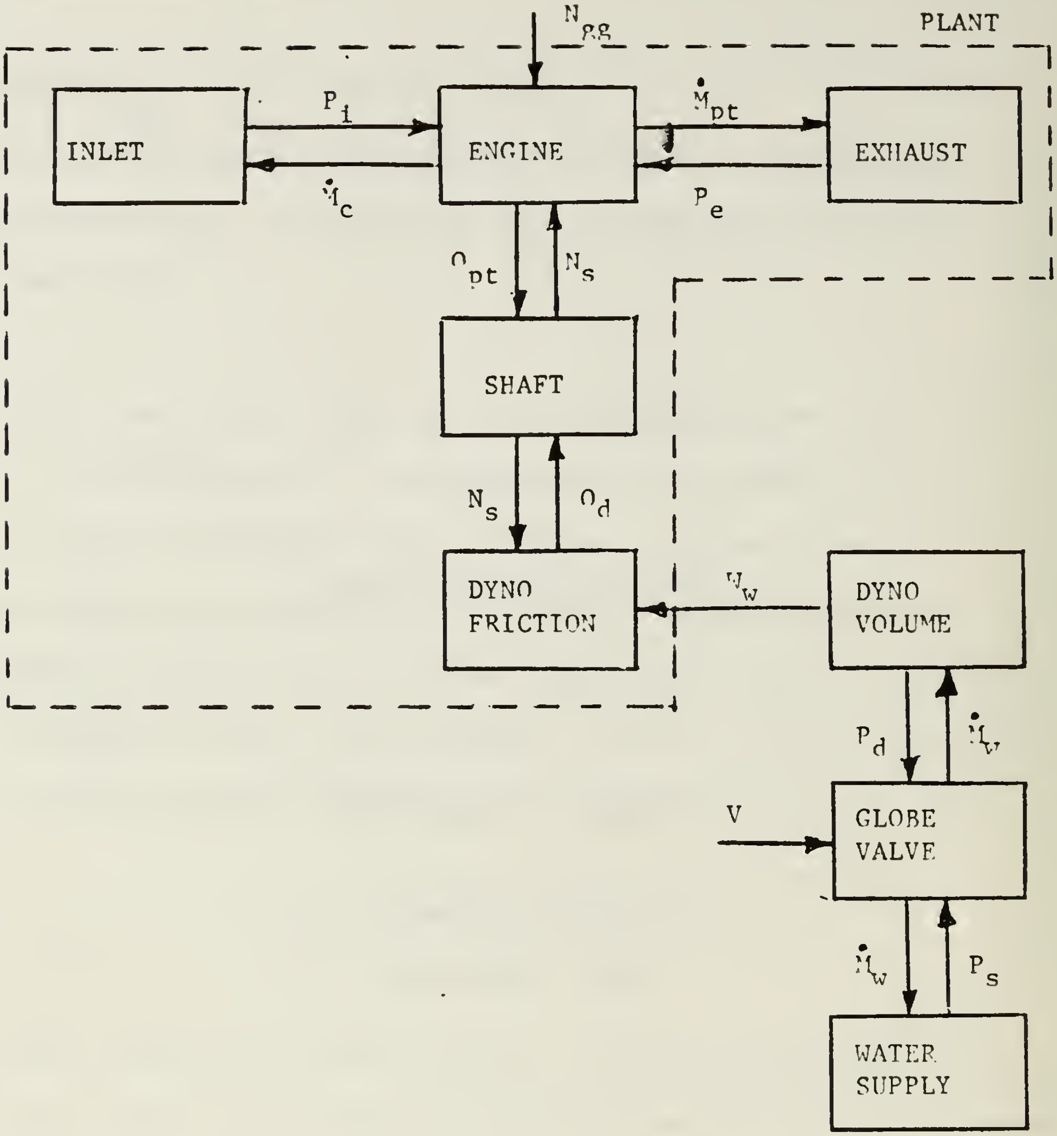
Open Loop Simulation

Linear MIMO Plants.

2 August 1985

due

9 August 1985



Introduction

In this two-part lab project we will begin to look at multivariable control as it applies to the emulator system. The system shown in the figure above contains the dynamometer plant and three components which are used as control actuators. Notice that the dynamometer is separated into two components: the "DYNO FRICTION" component represents the dissipation of mechanical power through fluid viscous effects, and the "DYNO VOLUME" component represents the internal water volume of the unit. Notice that one-half of the dynamometer is modeled in the plant while the other half is modeled in the controller. Recognition of this effect creates a very desirable control design situation since the controller can thus exert change on the plant without being effected in return. Such high impedance connections offer an excellent place to separate the controller and plant for design purposes. The water flowrate to the dynamometer is adjusted by a controllable globe valve which is connected to a regulated water supply. Thus, the system inputs are N_{gg}, the gas generator speed, and V, the valve opening. The following new variables appear in the figure:

$\dot{M}_w$	=	mass flowrate, lb_f/sec of water
P_d	=	dyno water pressure, psig
P_s	=	water supply pressure, psig
V	=	valve opening, in.

The objectives of this two week lab are the following:

1. To formulate multivariable system models for the components shown in the figure above. State variable and transfer matrix models will be considered.

2. To investigate the response of the system to changes in inputs.

3. To design a controller for the system based upon the transfer matrix model.

In this weeks assignment we will use a mathematical approach to formulating a state space model for the system, and then investigate the predicted response to inputs via CSMP.

In extending our earlier work, it can be shown that the following linearized model describes the dynamics of the plant

$$\dot{n}_s = 0.2\, n_{gg} - 20.n_s - 4000.0\, w_w .$$

Note the lower case of the variables, these are perturbations. A model for the dyno volume comes from the mass continuity equation

$$W_w = \int \dot{W}_w \, dt.$$

The NPS gas turbine dynamometer has been equipped with a regulated air pressure source to simplify the analysis and control design problems. When the air is turned on, the pressure in the dyno is $P_d = 4$psig. The valve component can be modeled with the standard orifice flow equation

$$\dot{M}_w = K_v\, V \sqrt{(P_s - P_d)}$$

with P_s = 40psig = constant, it's also regulated

and K_v = 1/6 $lb_f^{\frac{1}{2}}$/sec

This assignment is as follows:

1. Obtain the state equation in the standard form

$$\dot{\underset{\sim}{x}} = \underset{\sim}{A}\, \underset{\sim}{x} + \underset{\sim}{B}\, \underset{\sim}{u}.$$

That is, what are the entries in $\underset{\sim}{A}$? and $\underset{\sim}{B}$? In order to do this, you should work in perturbational variables, e.g., v (lower case) is one input while n_{gg} is the other. Also find the entries in $\underset{\sim}{C}$ and $\underset{\sim}{D}$ for the output equation

$$\underset{\sim}{y} = \underset{\sim}{C}\,\underset{\sim}{x} + \underset{\sim}{D}\,\underset{\sim}{u},$$

if

$$\begin{bmatrix} y_1 \\ \\ y_2 \end{bmatrix} = \begin{bmatrix} n_s \\ \\ w_w \end{bmatrix}.$$

2. Use the INTGRL statement of CSMP to integrate $\dot{\underset{\sim}{x}} = \underset{\sim\sim}{Ax} + \underset{\sim\sim}{Bu}$ and plot the following:

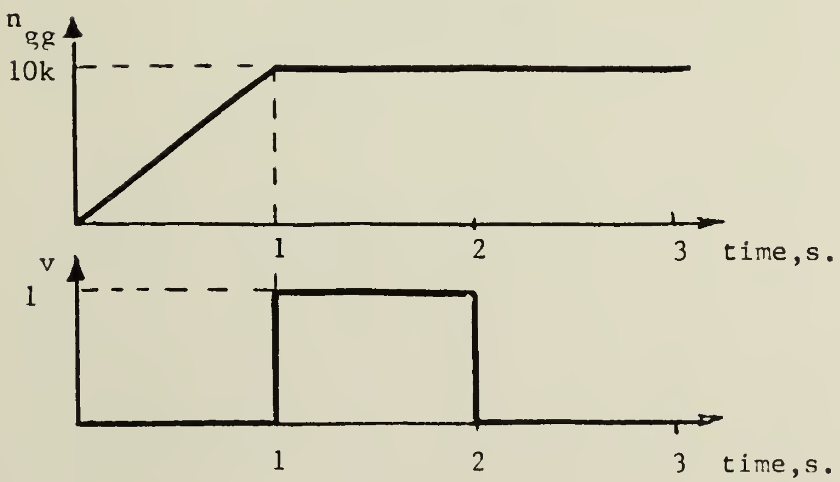
$$Y_1 = y_1 + Y_{1i} = n_s + N_{si}$$

$$Y_2 = y_2 + Y_{2i} = w_w + W_{wi}$$

for $N_{si} = 1500$ rpm

$W_{wi} = 3.5\ lb_f$

for the following inputs



3. If N_{gg} is held constant and a step input is given to V, under what mathematical conditions would it be possible to observe an oscillating response in N_s ? Can a corressponding physical condition occur?

ME 4802

MARINE PROPULSION CONTROL

Project 2 - Second Week

Transfer Matrix Design

9 August 1985

due

16 August 1985

This week we will conclude the plant multivariable modeling task and design a compensator for the transfer matrix model. There are three parts to this assignment:

1. Work problems B-14-3 and B-14-9 in Modern Control Engineering, pgs 713,715.

2. Last week you found a state-space model for the NPS marine propulsion emulator system of the form

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \dot{n}_s \\ \dot{w}_w \end{bmatrix} = \begin{bmatrix} -20 & -4000 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} n_s \\ w_w \end{bmatrix} + \begin{bmatrix} .2 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} n_{gr} \\ v \end{bmatrix},$$

with $$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$$

Use these relationships to find the transfer matrix $\underset{\sim}{G}_p(s)$ which models the emulator system above, e.g., $\underset{\sim}{y}(s) = \underset{\sim}{G}_p(s)\underset{\sim}{u}(s)$.

3. Design a compensator $\underset{\sim}{G}_c(s)$ so that the operator can control each output independently, and such that the following time constants are realized in each control channel:

$$n_s \text{ lag } = 3\text{sec.}$$

$$w_w \text{ lag } = 10\text{sec.}$$

That is, design $\underset{\sim}{G}(s)$ so that

$$\underset{\sim}{y}(s) = \underset{\sim}{G}(s)\underset{\sim}{r}(s),$$

where $$\begin{bmatrix} v_1(s) \\ v_2(s) \end{bmatrix} = \begin{bmatrix} n_s \\ w_v \end{bmatrix} = \begin{bmatrix} \frac{1}{3s+1} & 0 \\ 0 & \frac{1}{10s+1} \end{bmatrix} \begin{bmatrix} n_{sdes} \\ v_{wdes} \end{bmatrix}.$$

Sketch the block diagram of the controlled system showing how each input channel is processed by the controller(i.e., like figure 14-9, pg.691 Ogata).

ME 4802

MARINE PROPULSION CONTROL

Project 3 - First Week

Linearized Stability Analyses

16 August 1985

due

23 August 1985

The third, and final, lab project will extend over the last five weeks of the quarter. The project will consist of designing an optimal controller for the [illegible] gas turbine propulsion emulator. Five steps will be taken to the final design:

1. Develop an understanding of stability in MIMO systems.
2. Conduct preliminary plant model evaluations - study plant controllability and observability.
3. Perform a Linear Quadratic Regulator (LQR) design.
4. Determine LQR implementation strategy.
5. Conduct LQR design validation through closed-loop simulation.

This week we will lay the foundation for understanding the LQR design process by investigating the stability of MIMO systems (task 1 above). In the following weeks, we will address the remaining steps in the list.

This weeks assignment is composed of four parts:

1.) Given

$$\underset{\sim}{P} = \begin{bmatrix} 1 & 1 & 3 \\ 1 & 2 & 1 \\ 3 & 1 & 1 \end{bmatrix}$$

is $\underset{\sim}{P}$ positive definite? (show your work)

Also, if $V(\underset{\sim}{x}) = \underset{\sim}{x}^T \underset{\sim}{P} \underset{\sim}{x}$, is $V(\underset{\sim}{x})$ positive definite?

2.) Work problem B-15-2 in Modern Control Engineering.

3.) Given

$$\dot{\underset{\sim}{x}} = \underset{\sim}{f}(\underset{\sim}{x}) = \begin{bmatrix} x_1 \\ x_1^2 + x_2 \end{bmatrix}$$

use Krasovskii's Theorem to investigate the stability of the system near the origin ($x_1 = 0$, $x_2 = 0$).

4.) Linearize the system in (3) above about the origin and compare the linearized conclusion with the above nonlinear conclusion.

ME 4802

MARINE PROPULSION CONTROL

Project 3 - Second Week

Optimal Control:

Controllability and Observability

23 August 1985

due

30 August 1985

This week we prepare to begin the optimal controller design process. The design technique uses a time-domain state-space model of the standard form

$$\dot{\underset{\sim}{x}} = \underset{\sim}{A}\,\underset{\sim}{x} + \underset{\sim}{B}\,\underset{\sim}{u}$$

$$\underset{\sim}{y} = \underset{\sim}{C}\,\underset{\sim}{x} + \underset{\sim}{D}\,\underset{\sim}{u}.$$

Note that this is a linearized, perturbational model of the plant.

Following the identification of the state-space plant model, it is important to evaluate the sufficiency of the <u>model</u> before the controller is designed. Two questions about the plant model must be answered: Is the model controllable? and, Is is observable? Since the vast majority of physical plants are controllable, it is safe to assume that a proper model of the plant should also be controllable. Also, we know that the chosen state-space model is not unique for the given plant. Consequently, we must determine whether or not we have chosen a proper model form. For controllability, we determine if changes in the plant inputs properly affect the plant outputs. If they do, then the plant model reflects the controllability of the real physical plant.

An observable plant model is one from which we can determine the states $(\underset{\sim}{x})$ based upon output measurements $(\underset{\sim}{y})$. Clearly, for control purposes we need to have an adequate number and type of sensor measurements $(\underset{\sim}{y})$ in order to provide feedback for a regulator/controller.

The purpose of this week's assignment is to gain familiarity with the two preliminary plant model evaluations of controllability and observability as discussed in class. The assignment has four parts:

1. Work problem B-16-1 in Ogata.

2. Work problem B-16-4 in Ogata.

3. Work problem B-16-5 in Ogata.

4. Assess the output controllability and observability of the model of the NPS gas turbine propulsion emulator:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \dot{n}_s \\ \dot{w}_v \end{bmatrix} = \begin{bmatrix} -20 & -4000 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} .2 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

with $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$

Does your result agree with the test determined in B-16-4 above?

ME 4802

MARINE PROPULSION CONTROL

Project 3 - Third Week

LQR Designs

30 August 1985

due

6 September 1985

Last week we studied the preliminary evaluations of controllability and observability of state-space plant models. Once these determinations are made, it is possible to begin the optimal controller design process. This week we will design several Linear Quadratic Regulators (LQRs) for use in SISO and MIMO systems. The assignment has three parts:

1. Work problem B-16-11 in Ogata.

2. For the NPS gas turbine propulsion emulator model used last week, design an LQR controller based on the following performance index

$$J = \int_0^{\infty} (\underset{\sim}{x}^T \underset{\sim}{Q} \underset{\sim}{x} + \underset{\sim}{u}^T \underset{\sim}{R} \underset{\sim}{u})\, dt,$$

with the following weighting matricies

$$\underset{\sim}{Q} = \begin{bmatrix} 100 & 0 \\ 0 & 1 \end{bmatrix} \qquad \underset{\sim}{R} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

Use the approximate methods developed in class to estimate the $\underset{\sim}{P}$ matrix. Sketch a block diagram which shows how the controller processes the state measurements to produce the plant input signals.

3. Repeat 2 for the following weighting matricies

$$\underset{\sim}{Q} = \begin{bmatrix} 1 & 0 \\ 0 & 100 \end{bmatrix} \qquad \underset{\sim}{R} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

ME 4802

MARINE PROPULSION CONTROL

Project 3 - Fourth Week

Control

Implementation

9 September 1985

due

13 September 1985

In this weeks lab we will investigate several issues of the control implementation design process. In this work we will assume that the controller has been designed already in continuous time and we are concerned about the effect that descretization will have on system performance. The assignment has three parts:

1. Given an eight bit ADC, with a maximum input signal of $y_{max} = 10$volts, convert the input $y = 6.316$volts to its corresponding digital representation. What is the largest error that the ADC will produce in general?

2. Convert the following PID controller to its approximate impulse transfer function form, D(z), using a backward difference relationship for z:

$$G(s) = 10(1 + 5s + \frac{1}{10s}).$$

What is the controller recursion formula for this approach?

3. Several weeks ago we found the following relationship for the compensator which we designed for the NPS propulsion emulator:

$$\underset{\sim}{C}_c(s) = \begin{bmatrix} \frac{0.6(s+20)}{s} & \frac{6666.7}{s} \\ 0 & 0.1 \end{bmatrix}$$

Use Euler's method to find the approximate $\underset{\sim}{D}_c(z)$, and use $\underset{\sim}{D}_c(z)$ to find the controller recursion formulas for each control channel, u_1 and u_2.

ME 4802

MARINE PROPULSION CONTROL

Project 3 - Fifth Week

Optimal Control:

LQP Approach,

Closed Loop Simulation

13 September 1985

due

20 September 1985

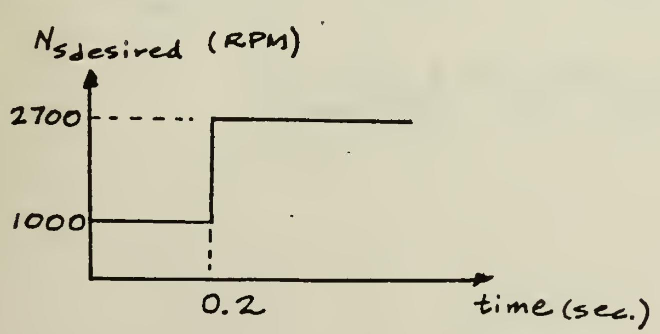
In general, it is not always possible to measure all the states for an LQR state controller. This means that the control designer will be faced with the problem of designing an observer that can estimate the state values based on the available measurement data. In class, this problem was considered for the NPS propulsion emulator where the only avialable state was N_s, the shaft speed. The observer was designed to estimate both N_s and W_w based on knowledge of N_s alone (plus the plant model).

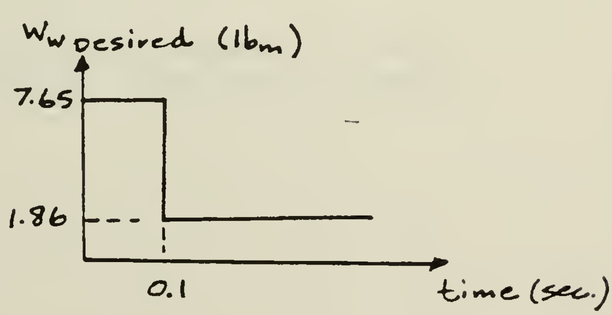
This assignment has two parts: first(required), repeat the design process for the observer for the NPS LQR digital controller designed in class using the value of sampling interval T = 1.0sec.; and second (optional), simulate the performance of the closed loop NPS LQR system for the two cases of weighting matricies and the two sample intervals as follows,

case 1 $\quad \underset{\sim}{Q} = \begin{bmatrix} 100 & 0 \\ 0 & 1 \end{bmatrix}, \quad \underset{\sim}{R} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad T = 0.01, \text{ and } 1.0\text{sec.}$

case 2 $\quad \underset{\sim}{Q} = \begin{bmatrix} 1 & 0 \\ 0 & 100 \end{bmatrix}, \quad \underset{\sim}{R} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad T = 0.01, \text{ and } 1.0\text{sec.}$

For the first part of the assignment, identify the entries in the $\underset{\sim}{G}$, $\underset{\sim}{H}$, and $\underset{\sim}{K}_o$ matricies. Choose the observer eignvalues to be separate and real. For the second part of the assignment, you may find the attached CSMP discussion useful. The system inputs should be





APPENDIX IV

PROPOSED EXPERIMENTS

I. Hydraulic Actuator Static Performance

Goals: Determine the static performance of a typical rotary actuator (pump driven motor).

Tests: (a) Motor shaft locked, zero return pressure. Measure internal and external leakage rates (by collection and timing) at various supply pressures.

(b) Motor shaft free and unloaded, controlled return pressure. Measure starting (breakout) pressure and running pressure at various return pressures.

(c) Motor shaft free and unloaded, zero return pressure. Measure forward pressure vs. shaft speed.

Data Reduction: Estimate internal and external leakage coefficients, internal friction coefficients (static and running), damping coefficient. Calculate volumetric, torque, and overall efficiencies as function of motor speed and forward pressure.

Facilities required:

1. Instrumented flow bench and system hydraulic supply.

2. Motor (e.g. fixed displacement piston type), forward and return pressure at motor ports, flow rate on return side, motor shaft speed.

II. Flow control valve static performance

Goals: Characterize a flow control valve of typical configuration (e.g. four-way, three-land, critical center or open center spool valve).

Tests:

1. Valve characterization. Determine spool dimensions, area gradient, underlap (if any), etc.

2. Measure null characteristics (flow vs. high and low-side pressure drops with spool centered).

3. Conduct flow versus pressure drop tests over range of fixed spool displacements from full open to full closed.

4. Compare results with theory. Estimate valve flow gains, flow-pressure coefficients, pressure sensitivies at null and show dependency on load pressure drop.

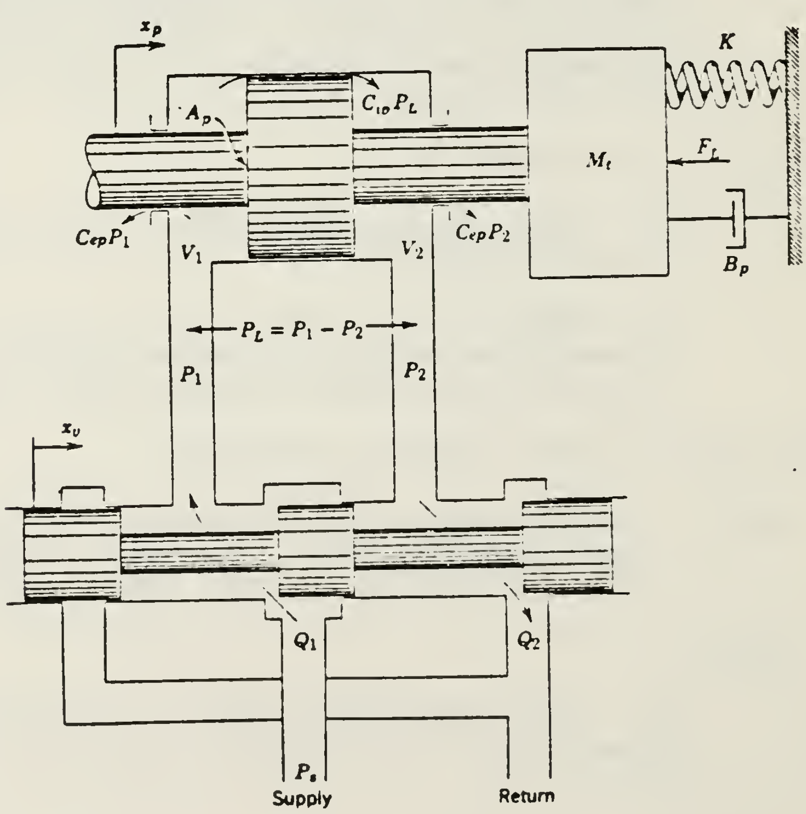
Facilities required:

1. Instrumented flow bench and system hydraulic supply.

2. Control valve with provisions for manual spool positioning and access to pressure measurement in supply and return chambers.

3. Flow metering. Both high and low pressure capabilities are desireable.

III. Dynamic performance of a hydraulic power element - valve controlled piston.



Goals: To evaluate the performance of the hydraulic power element, determine its performance characteristics (leakage coefficients, hydraul-spring rate, damping ratio, etc.) and compare these results with theory.

Tasks:

1. Determine necessary parameters: actuator volume, mass, contained volume, displacement,...)

2. Conduct frequency response tests with no applied load. Determine hydraulic natural frequency and damping ratio at various supply pressures. Examine the effects of crossport leakage and other design modifications.

3. Conduct stiffness (compliance) tests with valve stroke fixed and sinusoidal load inputs.

4. Compare results with theory.

Facilities required:

1. Instrumented flow bench and system hydraulic power supply (constant controlled supply pressure at variable flow rates).

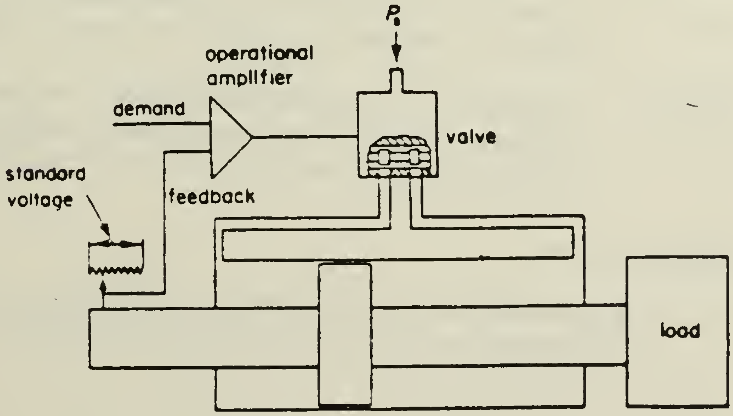
2. Hydraulic control valve with valve displacement controlled and measurable (valve used in Experiment II if suitable).

3. Mechanism for sinusoidal valve stroke input (can be home-made).

4. Mechanism for sinusoidal load input.

5. Transducers for valve and load displacement, load force, and suitable recording/processing equipment.

IV. Position Control Servomechanism



Goals: Examine the dynamic performance of the servo and evaluate the effects of various design options. Compare observations with predictions.

Tasks:

1. Determine bandwidth and stability characteristics, etc.

2. Examine the effects of under- and over-damping, load variations, spring loads, non-linearities. Induce and correct limit cycling, etc.

Facilities:

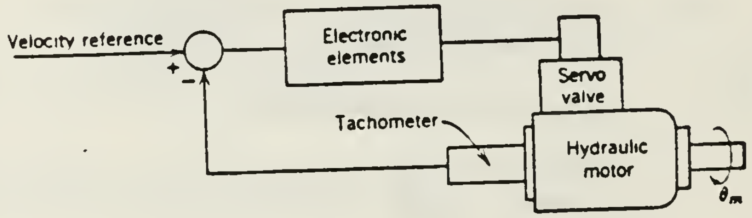
1. Flow bench with constant pressure supply.

2. Position control servomechanism. Valve-controlled ram with two-stage electrohydraulic servovalve, position feedback, servoamplifier.

3. Controllable load.

Note: These facilities should be as accessible to the user as possible. E.g. variable feedback gain, variable load damping, variable gain in pilot stage, etc.

V. Velocity Control Servomechanism



Goals: Determine system performance characteristics and the effects of various design options.

Tasks: Similar to experiment IV. with the addition of lead-lag compensation experiments and the effects of gear ratio at the load.

Facilities:

Same as in experiment IV but utilizing a rotary system and controlling velocity instead of position.

FLUID POWER CONTROLS LABORATORY

Estimated Equipment and Materials Requirements:

Item	Estimated Cost
1. Fluid power bench including:	
a. Working surface for setup and conduct of experiments. Includes mounting accomodations and excess fluid drainage to waste sump.	
b. Instrumented panel showing operating status of fluid power supply: Inlet and return pressures, sump temperature, return temperature, return flow rate.	
c. Additional pressure gages for indication of tapped pressures up to system maximum pressure.	
d. Hydraulic power supply with constant pressure control and operable at 10 gpm and 1500 psi supply pressure.	
e. Reservoir with capacity of 33 Gal. Minimum and provision for fluid temperature control.	
f. Electric drive for above at 230/460v, 60Hz, 3-phase.	
g. Suitable pressure connections for coupling experimental pressure to panel-mounted gages. All connections to be of low pressure-drop type.	
h.	
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Item	Estimated Cost
2. Fluid power actuators suitable for operation at system capacity.	
a. Piston	
b. Motor	
i. Piston type	
a. Fixed Disp.	
b. Var. Disp.	
ii. Vane type, Fixed Disp.	
iii. Gear type	
3. Flow control valve - for Exps. II, III. 4-way, 3-land, critical (or open) center spool valve with externally controlled spool position and internal chambers accessible for pressure taps.	
4. Electrohydraulic Position Control Servomechanism consisting of: Servovalve, Actuator (piston), Load position feedback. Items may be integral or separate.	
5. Electrohydraulic Velocity Control Servomechanism consisting of: Servovalve, Actuator (motor), Load velocity feedback. Items may be integral or separate.	
6. Servo-amplifier suitable for application to items 4. and 5. above. Amplifier should provide for easy change of feedback and feed forward gains, and selection of position or velocity control inputs.	
7. Transducers:	
a. Direct pressure, 0-1500 psia	
b. Differential pressure, 0-800 psia.	
c. Flow- high pressure	
d. Flow- low pressure (bench mounted rotameter in return line)	

Item	Estimated Cost
8. Storage facilities:	
a. Cabinet for storing hydraulic hoses, connectors, etc.	
b. Cabinet for storage of valves and actuators.	
c. Cabinet for storage of sensors, transducers, and other electronic gear.	
9. Table working surfaces extending, in segments, for approximately 18 feet.	

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